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Study on the Application of the Shock Model in Forecasting Residual Life of CNC System

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Currently, the development of CNC machine tool changes rapidly and it sets efficient, flexible and sophisticated composite many of the advantages of an equipment manufacturing in a body so that the CNC machine tool has become the main processing equipment and mainstream products. The failure will seriously affect the competitiveness of the market if the equipment failure. However, fault diagnosis technology plays an important role in the maintenance of equipment and products, fault diagnosis research has gradually focus on condition monitoring, predictive maintenance and early fault diagnostic. The new concept is the use of intelligent maintenance system (IMS), constantly monitoring the status of equipment and product performance, forecasting and assessing, make a maintenance plan to prevent them from fault. The core technology of IMS is predicting and assessment the performance degradation process of the equipment and products. Shock model is one of the important researches in the reliability mathematical theory and describes system failure, maintenance and so the phenomenon of life in randomly changing environment whose central issue of the research is system failure or system life. This article discusses a shock model that the times of shock is a Poisson process and the damage is additive, obtain the expectations of damage combined with the failure characteristics of the CNC system, and provide a basis to assess the residual life of the CNC system.

1. Introduction

CNC system is the core control parts of CNC machine tools, which reliability directly related to the level of reliability of CNC machine tool (Keller and Kamth et al., 1984). It is an important basis to predict the remaining life of the product for its maintenance, replacement and development of spare parts strategy (Peng and Zhou et al., 2011). Life prediction methods generally use only the data of the performance degradation of the product itself when less performance degradation data. However, it is difficult to guarantee the accuracy of the predicted results of the remaining life.
Shock model is one of the important researches in the mathematical theory of reliability, which is generally used to describe the system failure, maintenance and other life phenomena in random changes in environment. The one of center problems of the shock model research is system failure time or system life. Based solely on the deterioration or random shocks to discuss the reliability of the system is widely mentioned in various literatures. Esary (1973) have studied the life distribution of the system and obtained the nature of the IFR, IFRA and NBU of the survival function when the basic process is homogeneous Poisson process. Gut (2009) has studied the system life of the cumulative model using stopped random walks theory, and then pointed out the application of model in the insurance risk theory. With regard to system failure mechanism, the three basic types (Nikulin, 2010) are mainly taken into account: (1) Successive cumulative shock values fall into a parameter region due to system failure; (2) The strength of a single shock falling into a parameter region caused system failure; (3) Continued with the intensity of the k shocks falls on a parameter region due to system failure. This article discusses the shock model that the times of the shock follows a Poisson process and the damage is additive. And then the failure

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characteristics and causes of a CNC system are analyzed and the expected damage is obtained, which provides a basis to assess the residual life of the CNC system.

2. Shock model

Shock model are systems that at random times are subject to shocks of random magnitudes. One distinguishes between two major types; cumulative shock models and extreme shock models. Systems governed by the former kind breakdown when the cumulative shock magnitude exceeds some given level, whereas systems modeled by the latter kind breakdown as soon as individual shock exceeds some given level. Another shock model which is based on a run of k critical shocks was introduced in (Mallor and Omey, 2001) with $k > 1$. If $k = 1$, their model reduces to the extreme shock model.

2.1 Poisson process

Definition 1(Tang and Xu, 2007) the counting process is Poisson process, if it satisfies

$$\begin{cases} N(0) = 0, \\ P\{N(h=1)\} = \lambda h + o(h), \\ P\{N(h \geq 2)\} = o(h). \end{cases} \tag{1}$$

The probability that events occur once is proportional to the length of the time interval, while in a small time interval the event cannot appear twice or more. In practical problems, a lot of random phenomena are approximate to meet these two conditions and this can be described in a Poisson process.

Let X_1 be the arrival time of the first event, $X_n(n>1)$ represents the time interval of the $n-1$ -th event and the n -th event arrives.

Theorem 1 the arrival time interval sequence $\{X_n,(n>1)\}$ of λ Poisson process $\{N(t),t\geq 0\}$ is an independent random variables sequence which follows exponential distribution with same mean $1/\lambda$.

Let S_n represent the time of the n -th event, that is $S_n=X_1+\cdots+X_n$, S_n is called the wait time until the n -th event and also known as the time of arrival.

Theorem 2 (Liu, 2004) the wait time S_n follows Γ distribution with the parameters n and λ .

Definition 2 Specimen $Y_1,\cdots,Y_n$ is rearranged $Y_{(1)},\cdots,Y_{(n)}$ from small to large and then $(Y_{(1)},\cdots,Y_{(n)})^T$ is called the order statistics of $(Y_1,\cdots,Y_n)^T$, $Y_{(k)}$ is the k -th order statistics, $Y_{(1)}$ is the smallest order statistics, $Y_{(n)}$ is the largest order statistics.

Theorem 3 (Liu and Wang, 2004) If the density function of Y distribution is $f(y)$ (or the distribution function is $F(y)$) and $Y_1,\cdots,Y_n$ is a sample from the overall, then the density of the k -th order statistics $Y_{(k)}$ is

$$f_{Y_{(k)}}(y)=\frac{n!}{(k-1)!(n-k)!}\times[F(y)]^{k-1}\times[1-F(y)]^{n-k} f(y),k=1,\cdots,n \tag{2}$$

Theorem 4 If the density function of Y distribution is $f(y)$ (or the distribution function is $F(y)$) and $Y_1,\cdots,Y_n$ is a sample from the overall, then the joint density of $(Y_{(1)},\cdots,Y_{(n)})^T$ is

$$f(y_1,\cdots,y_n)=\begin{cases} n!\prod_{i=1}^{n} f(y_i),y_1<\cdots<y_n \\ 0,\text{orthers} \end{cases} \tag{3}$$

Theorem 5 If $N(t)=n$, then the joint density function of arrival event of n events is equal to the density function of n independent order statistics of random variable with $[0,t]$ uniform distribution.

2.2 Shock model

If a component is subject to random shocks, the number of times $N(t)$ in $[0,t]$ is λ Poisson process, here, the i -th shock damage is the random variable $D_i(i=1,2,\cdots)$, D_i is independent and identically distributed and independent with $\{N(t),t\geq 0\}$. Because the damage caused by shock usually decrease exponentially by time, we assumed that the initial value for each shock is D , and the damage is De^{-at} after time t , here a is a positive constant. If we assume that the damage is added, total damage from the beginning until the time t is $D(t) = \sum_{i=1}^{N(t)} D_i e^{-a(t-S_i)}$, here S_i represents the arrival time of the i -th shock.

$$E[D(t)\,|N(t)=n] = E[\sum_{i=1}^{n} D_i e^{-a(t-S_i)}|N(t)=n]$$
$$= \sum_{i=1}^{n} \{E[D_i|N(t)=n]E[e^{-a(t-S_i)}|N(t)=n]\} = E[D_1]e^{-at}E[\sum_{i=1}^{n} e^{aS_i}\,|N(t)=n] \quad (4)$$

Let $U_1,\cdots,U_n$ be mutually independent random variables with uniform distribution, we can be obtained by Theorem 5

$$E[\sum_{i=1}^{n} e^{-aS_i}|N(t)=n]=E[\sum_{i=1}^{n} e^{aU(i)}]=nE[e^{aU_1}]=\frac{n}{t}\int_0^t e^{ax}dx=\frac{n}{at}(e^{at}-1) \quad (5)$$

$$E[D(t)|N(t)=n]=E[D_1]e^{-at}\frac{n}{at}(e^{at}-1)=\frac{n}{at}(1-e^{-at})E[D_1] \quad (6)$$

$$E[D(t)]=\frac{EN(t)}{at}(1-e^{-at})E[D_1]=\frac{\lambda E[D_1]}{a}(1-e^{-at}) \quad (7)$$

If the system damage reaches constant A , the damage time to the system is $t=\min\{t{:}E[D(t)]\geq A\}$. It is difficult to calculate, but it can be approximated as

$$\hat{t}=\min\{t{:}E[D(t)]\geq A\}=\min\{t{:}\frac{\lambda E[D_1]}{a}(1-e^{-at})\geq A\} \quad (8)$$

3. Failure characteristics of CNC system

CNC system is the core of CNC machine tools and its reliable operation is directly related to that the entire device is operating normally or not. The kinds of our existing numerical control system of CNC machine tool is extremely numerous, there are domestic CNC systems, but also the systems from all over the world, such as FANUC system, FAGOR system, Siemens system, the Mitsubishi system, Guangzhou NC and so on. The systems of various types have the uneven complexity, different functions and have a variety of structural styles.

Failure mode and effects analysis (FMEA) of CNC system is an important work of the reliability study, and the analysis results also lay the foundation for the realization of the reliability growth of CNC system. Only failure analysis of the CNC system, we can find out the failure causes and then come up with effective prevention and improvement measures to ensure the healthy operation of the CNC system and improve the reliability of CNC system.

A CNC-SRT laboratory has been established in Beihang University. Because failure analysis is based on a large number of fault data, 30 sets of CNC system have been selected to observe and then extract the fault data related to the CNC system. The reliability laboratory of the CNC device and the detection system of the reliability test are shown in Figure 1.

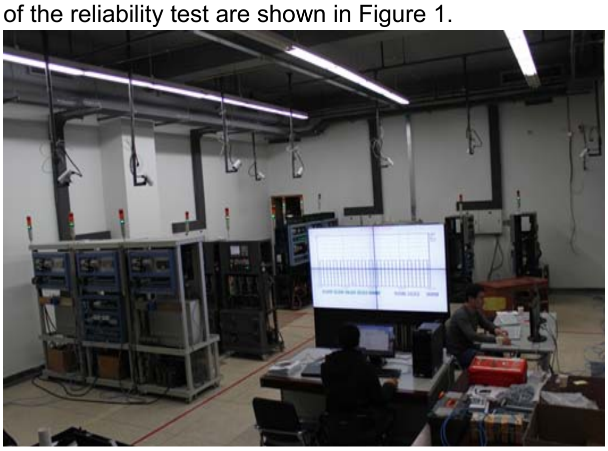

Figure 1: The reliability laboratory and the device of the CNC system

3.1 Failure characteristics of a CNC system

The division of the fault position is the foundation to analyze fault-prone parts and the prerequisite to define failure vest. In this paper, we have obtained that hardware parts failure of CNC system is relatively frequent from the collected fault information and the electrical system is the most prominent. The electrical system is composed by a variety of electronic components, including switches, relays, contactors and fuse, dispersed in various parts of the cabinet and the machine body. The reliability of the electrical system is closely related to working environment and environmental adaptability, the failure rate and environmental factors of most of the electronic components have changed exponentially. However, CNC systems often run in bad weather, mechanical environment, power environment, environmental conditions and electromagnetic interference environment, electrical systems prone to component damage, cable poor contact and the fuse breaker, etc., which led to that the reliability of electrical system is reduced and fault occurs frequently.

The failure of the PLC unit is a very close relationship with the model chosen and working environment, supply voltage fluctuations and momentary power outage, changes in temperature and humidity, vibration and noise shock will result in failure of the PLC unit. In addition, human operator error is the main reasons of failure-prone. Compared to hardware failure, the frequency of software failure is low and the reliability of the software is higher than the hardware. Most of the software failure is due to design error and system loopholes. Furthermore, the user is not familiar with all of the features of the CNC system, very easy to produce incorrect results or program to fail and which result in system failure.

3.2 Failure mode analysis of CNC system

Failure mode of the CNC system is defined as a state of CNC system failure with respect to a given predetermined function. Failure mode is not only the basis of analysis of the failure cause, but also is the basis of reliability design of the CNC system in the research and development. Failure modes of the CNC system have been analyzed, as shown in Table 1 (Zhang et al., 2004).

Table 1: The frequency of the failure mode

Failure mode	Frequency	Failure mode	Frequency
Component damage	0.23636	Output term deficit	0.01818
Poor line and cable connection	0.10303	Crash	0.01818
Processing program error	0.08485	Line, cable disconnect	0.01818
Execution error	0.07879	Detection system failure	0.01212
PLC disorders	0.07273	Position control not in place	0.01212
Components loss of function	0.06667	Not operate properly	0.01212
Loss of programs and parameters	0.04848	Component parameter drift	0.01212
CRT no display	0.04242	Components pin Weld	0.01212
Sensing component failure	0.04242	Excessive temperature rise	0.00606
Decline in performance parameters	0.03636	False Alarm	0.00606
Electromechanical match disorder	0.02424	Line cable short-circuit	0.00606
Fuse damage	0.02424	Excessive noise	0.00606

Component damage is most frequent among the failure mode of CNC system, including the damage of the display, electronic components, buttons and switches. Most components are largely damaged by environmental factors, with greater vibration and more fumes dust in the production and processing. Secondly, the failure mode appears more in bad line or cable connection and poor line connection often appears in the joint position. The most frequent failure mode of the software part is the machining program error. On one hand, a program error is caused by the CNC system itself, such as Relay contact switch discharge, a surge voltage generated by the electromagnetic coil, etc. When the power supply voltage fluctuations or instantaneous power failure, it makes program breakpoints cannot be saved when the program breakpoints, when the power is reset which makes that processing program cannot continue finally. On the other hand, a program error caused by the human operation, CNC technicians could not well understand and master CNC system which resulting in an error in the preparation of the machining program.

3.3 Failure cause analysis of CNC system

CNC system is a typical mechatronic system, with a large and complex structure, involving optical, machinery, electricity and multiple input and output signals, which make industrial field troubleshooting become quite complex and difficult. In this paper, the CNC system failure analysis has been obtained using the fault data collected, shown specifically in Table 2.

Table 2: Number of times and frequency of failure causes

No.	failure causes	Times	frequency	No.	failure causes	Times	frequency
1	Component damage	57	0.4790	1	Weld	1	0.0084
2	Overcurrent	18	0.1513	2	Misuse	1	0.0084
3	Short circuit	4	0.0336	3	Network fluctuation	1	0.0084
4	Improper adjustment	4	0.0336	4	Poor environment	1	0.0084
5	Overvoltage	3	0.0252	5	Unknown	1	0.0084
6	Overload	3	0.0252	6	Other	1	0.0084
7	Open circuit	3	0.0252	7	Miswiring	1	0.0084
8	Loose	3	0.0252	8	Parameter error	8	0.0672
9	Process bad	2	0.0168	9	Parameter missing	3	0.0252
10	Dead battery	2	0.0168	10	Loss of function	2	0.0168

It can be seen from Table 1, components damage is most frequent among the failure causes of the CNC system. Components damage can be attributed to two issues of its own and use. Components of poor quality and using too often are the main reasons for induced failure. The one hand, most of the components run and use for long-time and appear wear and fatigue cracks so that the components are easy to failure. On the other hand, the failure is caused by human because the technology of operator does not meet the requirements, not required to use and maintain the system. Weld is also the main reason for induction the failure and tends to occur in parts of the electrical connector or circuit board solder. On one hand, circuit board pads appear mechanical damage caused by the shock or vibration. On the other hand, solder joints virtual access is due to expansion coefficient change because of the circuit power outage or environmental changes. Program error is the main reason of the software failure, the robustness design of the software should be increased. Also, a better user interface should be provided for the technical staff, enable them to well use, maintain and develop the CNC system.

3.4 Analysis of fatigue crack

CNC system is the core of the electrical control system of CNC machine tools. Each machine running after a certain time, some components will appear some damage or malfunction.

Now a component of the CNC machine tools is taken as for study, using shock model to analyze the fatigue crack propagation, so that we can predict the residual life of the CNC system. Fatigue crack is a common degradation phenomenon for mechanical components. In this section, an example is given to illustrate the proposed models in Section II. This example is based on the fatigue crack data of an alloy in (Lu and Meeker, 1993). All samples have an initial crack length of 0.90 inch. The cumulative degradation of the fatigue crack data is shown in Figure 2. Wang (2011) and some other researchers have used the data to analyze the reliability of the component. Here we will use the same data to illustrate the proposed model and obtain the results.

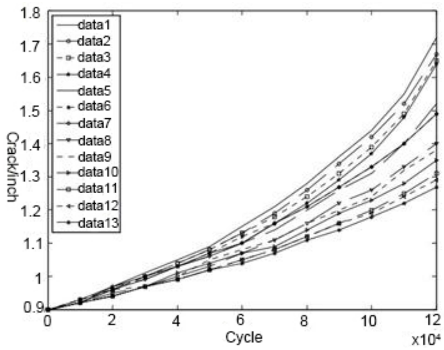

Figure 2: The cumulative degradation of fatigue crack sizes

4. Results and discussions

It is supposed that the random shock process follows a Poisson process, the shock damage size $D_i(i=1,2,\cdots)$ is assumed to follow a normal distribution and $D_i \sim N(0.02inch, 0.1inch)$; the failure threshold value $A=2.0$ *inch* and the occurrence rate is $\lambda=1.0$. So the reliability function $R(t)$ is shown as in Figure 3.

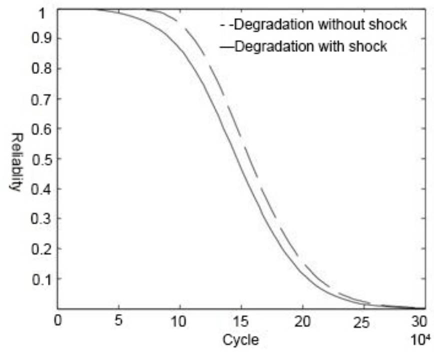

Figure 3: Plot of reliability under different case

As shown in Figure 3, the solid line is the reliability when the random shocks are accounted for and the dotted line is reliability that the random shocks are not considered. Obviously, the two curves begin to separate and the effects of shocks become larger. If the above values are substituted into equation 8, we can obtain equation 9 and get the residual life of the system by calculating.

$$t \geq \frac{1}{a} \ln \frac{20a-9}{9} \quad (9)$$

5. Conclusions

In this paper, we have established a reliability model for components subject to shock model and Poisson process. The random shock can cause an abrupt damage to the degradation process. The case study has shown that shocks have obviously impact on the reliability of the component, and the reliability is higher when the impact of shocks is not considered. Meanwhile, we have given a formula to calculate the residual life so that to predict the residual life of the CNC system by analyzing the failure characteristics of CNC system.

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